

Guidance Document

Controlling liquid metal assisted cracking during galvanizing of constructional steelwork

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1 Introduction

Liquid metal assisted cracking (LMAC), or liquid metal embrittlement (LME), occurs when a combination of steel characteristics, fabrication detailing and galvanizing processing variables create conditions for brittle cracking of a steel article during galvanizing. Such a combination of factors rarely occurs in practice.

For fabrications that might be susceptible to LMAC, it is recommended to follow the guidance contained in this document. This guidance augments the basic guidance given in Clause 6.5.5 of EN ISO 14713 Part 2: 2009¹ - which encourages control of the design (e.g. location of stress concentrations) and detailing of the component (e.g. steel quality, levels of residual stress, quality of welding, and position and finishing of drilled or punched holes and flame-cut surfaces), and the galvanizing conditions (e.g. pre-treatment conditions, dipping speed and zinc melt constitution).

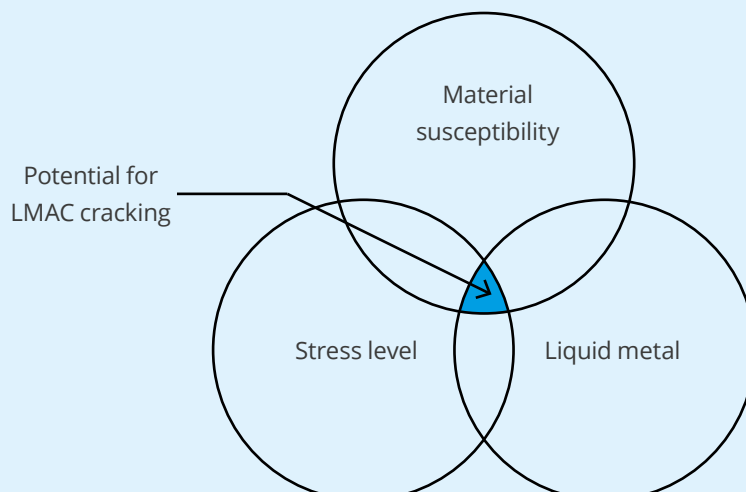
Recent experience demonstrates that (i) fabrication and detailing in line with EN 1090 Part 2; (ii) appropriate design for galvanizing in line with EN ISO 14713 Part 2 and (iii) galvanizing to EN ISO 1461 are the principal pre-requisites for avoidance of LMAC. However, attention to additional controls should be considered for fabrications that might be susceptible to LMAC.

Nowadays, examples of LMAC that are observed in practice are usually caused by faults in fabrication that can be simply avoided through adherence to requirements of EN 1090 Part 2 and associated good welding practice.

This guidance may also be used to support the Factory Production Control systems associated with EN 1090 that may be operated by a Steelwork Contractor with the support of the Galvanizer.

1.1 A basic explanation of liquid metal assisted cracking during galvanizing

LMAC can occur as a result of the convergence of a number of adverse factors as described by the below diagram:



1.1.1 Material (Steel)

Batch galvanizing is successfully applied to a wide range of steel grades that exhibit a range of mechanical properties. Some of these properties, notably notch toughness, have a significant effect on susceptibility to LMAC. Variations in notch toughness between steels of the same grade and within a given steel component are known to exist. However, in preparing this guidance, these variations must be accepted and accommodated through control of other parameters, such as galvanizing process parameters and fabrication detailing.

1.1.2 Stress during galvanizing

LMAC (ie penetration of grain boundaries by liquid metal leading to brittle fracture) will not occur without the presence of (tensile) stress at the steel/liquid metal interface. The source of this stress is two-fold:

- Residual stress in the component created by manufacture (e.g., rolling) or fabrication (e.g., welding)
- 'Induced' stress created by the differential thermal expansion/contraction of the steel component during galvanizing.

In the presence of more aggressive liquid metal environment, it is the peak value of strain that is likely to drive crack initiation.

1.1.3 Liquid Metal Environment

The presence of a liquid metal, such as zinc, is a pre-requisite for LMAC to occur. It is known that the presence of certain alloying elements in the galvanizing bath has a significant effect on the occurrence of LMAC. The role of these alloying elements is thought to be two-fold. The alloying elements themselves, or eutectic compositions of alloys with other elements, have reduced solubility in liquid zinc and concentrate at the steel-zinc melt interface. These compositions may (i) be more aggressive for grain boundary penetration and (ii) increase heat transfer to the immersed section of the component with an increase in differential thermally-induced stresses in the component.

1.1.4 Time

The duration of exposure to high stress / strain during galvanizing ('holding time' in the galvanizing bath) can have an effect on LMAC occurrence.

1.2 Principles for Control of LMAC

This guidance is based on the following principles:

- i. Optimise fabrication detailing to reduce the susceptibility of steel components to cracking (*mainly achieved through compliance with requirements of EN 1090-2*).
- ii. Identify design choices that increase susceptibility to cracking beyond that which can be controlled by optimal fabrication and galvanizing practice. Eliminate those design choices and/or ensure these designs are subject to suitable post-galvanizing inspection.
- iii. Control the galvanizing process to avoid process parameters that increase the susceptibility of steel components to cracking. Control of these parameters will significantly reduce the extent of additional requirements for fabrication detailing and widen the range of designs that are suitable for galvanizing.

2 Guidance – fabrication and structural detailing

2.1 General Guidance

Good practice in fabrication detailing and methods, such as those required by EN 1090-2, will reduce the risk of cracking during galvanizing. However, depending on the type of steel component and construction in which it is to be incorporated, it may be necessary to adopt particular detailing and fabrication practices such as 'radiusing' of notches, grinding and finishing, for example to further reduce the risk of cracking.

The Steelwork Contractor should ensure that the steel used conforms to the required specification and is not downgraded material from a higher specification, or steel from an unknown supplier.

Stress is clearly an important factor and any steelwork fabrication will contain residual welding stresses and residual stresses from rolling, cold deformation and heat straightening. In the hot dipping operation there are additional thermally induced stresses at levels dependent upon the 'overall local stiffness' of the component being dipped and the differential temperature and temperature gradients set up. Large changes in material thickness should be avoided, such as thin gussets on thick members, as this causes stress due to unequal heating rates of the steel component.

Steel members will be sheared, sawn or gas/plasma/laser

cut to size and shape introducing further residual stresses. There may be a need for large holes or shapes to be cut and these again will add to the final stress pattern in the fabrication.

Defects on components, such as surface damage from undercuts during welding and structural notches, should be avoided.

Compliance with EN 1090-2 will significantly reduce the risk of cracking. Conversely, failure to comply with this standard may also increase the risk of cracking.

2.2 Material selection and general design approach

The minimum grade of steel that will achieve the design requirements should be specified. Higher grade steels are regularly galvanized but may be more likely to exhibit LMAC due to their microstructure and rolling stresses (i.e. stresses induced during rolling to improve yield stress). Care should be taken in the design of member components, so that they do not require excessive stiffening at the connection nodes.

Unbalanced internal stress states and variation in local restraint (such as arise on half end-plate connections) should, if possible, be avoided in steel constructions to be hot dip galvanized and alternatives such as bolted connections or full depth end-plates should be used.

2.3 Components with different thickness

Substantial changes in material thickness at any point will induce large thermal stresses, when dipped into the galvanizing bath as the thinner material will heat up much faster than the thicker material. The ratio of maximum/minimum section thickness is recommended to be ≤ 5 . Where this ratio would be exceeded, bolted connection of the sub-components would be advisable.

Symmetrical cross-sections are more advantageous than asymmetrical ones as they help to balance out the inherent stresses.

2.4 Welding

To minimise welding stresses the Engineer should stipulate the minimum welding requirements (size, weld metal, heat input) and if possible arrange welding to be balanced. Fillet welds are better than butt welds for fitments such as brackets and secondary stiffening, and in some situations intermittent welding should be considered where appropriate. The use of intermittent welding is an excellent way to minimise welding stresses. It also avoids creating air pockets between members that can easily lead to a pressure build up [with trapped air/water/galvanizing pre-treatment fluids producing superheated air/steam at the galvanizing temperature].

Balanced welding patterns should be adopted, particularly for asymmetrical components. The welds should be as close as possible to the axis through the centre of gravity of the entire profile. If they are not, they should be as symmetrical

as possible, at the same distance from the axis through the centre of gravity and should be generated at the same time. Asymmetrical cross-sections constitute a greater risk of warping, especially if thicker welds are positioned on one side, at a greater distance from the axis through the centre of gravity.

2.5 Lattice and complex fabrications

In lattice-type and other complex fabrications, as few redundant members as possible should be adopted, as these will increase stresses and distortions throughout the component members when heated. However, the need to minimise redundancy should be balanced against an overall appraisal of robustness and then weighted carefully against the suitability of galvanizing for a complex component.

Components in which any internal static redundancy leads to high secondary stresses in the zinc bath should be avoided.

2.6 Cut Edges

Cut edges can act as origins for crack initiation based on

- (a) The method used for cutting them.
- (b) Position in the work-piece.
- (c) Quality of workmanship.

Mechanical (saw) cutting should not cause any problems as long as tools are in good condition and do not introduce local stress raisers such as sharp irregularities or notches. However, problems may occur when perpendicular cuts intersect and create a sharp angled corner. In such cases it is necessary to ensure that the point of intersection between the two cuts is of a smoothly curved profile with no irregularity or notch. This may be achieved by first drilling a hole of minimum diameter of 10mm and then cutting to the hole to provide a suitable radius.

Flame cutting can cause localised hardness variations which may act as stress raisers and a surface hardness of 380HV should not be exceeded. If there are any doubts that this value can be respected, a light surface grinding of the edges of the flame cut areas can remove this effect and minimise the risk of crack initiation. It may also be possible to use flame-softening in these areas (see 2.9).

Best practice in steel fabrication, whether galvanized or not, is that thermally cut re-entrant curves and notches shall be rounded off with a minimum radius of 5mm. It is also good practice to apply this rule when such cuts are made using mechanical methods. Special considerations are necessary in the "K- areas" of universal beams, where copes are cut (see 2.9). It is very important that these considerations are taken into account.

2.7 Holes

Holes may be drilled or punched. In either case it is important that tools are in good condition to ensure that

they are clean and smooth to avoid the creation of stress raisers.

Punching of holes can cause microcracks around the edge of the hole. However, because the punching process creates an area of localised compression, it is believed that these cracks are unlikely to propagate, whether the steel is subsequently galvanized or not.

Holes should not be drilled in the "K- areas" of Universal Beams and Columns. (See 2.9)

2.8 Location of Vent/Drain Holes for Galvanizing

Design guidance is contained within BS EN ISO 14713-2:2009 and this should be observed (as required by EN 1090-2, Clause 10.5). That guidance includes recommended minimum hole sizes, but it is always advisable to discuss this with the Galvanizer prior to fabrication, in particular for complex fabrications.

Holes should be as large as possible, correctly positioned and few in number. They are vital in enabling the Galvanizer to maximise speed of immersion in the zinc and to ease withdrawal as well as in helping to improve safety and product quality. Specific considerations exist with the provision of vent/drain holes in universal beams and columns when they have transverse stiffeners/plates (see 2.9).

2.9 Cope-Cutting and Other Work in "K-areas" of Universal Beams and Columns.

Because cope-cuts are made in the "K-area" of universal beams and columns, the material susceptibility to cracking in those areas can be increased.

There are significant variations in localised toughness and strength characteristics in the "K-areas" of universal beams and columns, with typically higher strength and lower toughness than exist within the flanges. This is a natural outcome of the manufacturing method and because the strength/toughness characteristics are measured in the flanges, is not critical for function.

However, for this reason, particular care needs to be taken over any work done in these areas. The most common feature associated with crack events in "K-areas" is cope-cutting.

Although the overall incidence of LMAC associated cracks is very low, statistical investigation over several years has shown that the most prominent design feature which is apparent within those statistics is cope-cutting. Cracks originating at cope cuts have been well investigated and appropriate precautionary practices are already proven to virtually eliminate the risk.

As described in section 2.6, cuts may be made by mechanical or thermal methods and the precautions referred to in section 2.6 should be applied. Because of the

particular characteristics of “K”-areas” described above, these precautions are the minimum requirement and further specific provisions should be considered:

- (a) If using mechanical methods, the practice of overcutting, filling in with weld material and then grinding is not recommended.
- (b) The minimum recommended radius for the curve² of the cut is 2.5cm.
- (c) A smoothly curved cut profile with no notching or irregularity is essential.
- (d) It has been established that flame-cutting may create a significant hardness gradient, giving a local increase in material susceptibility³. The removal of any localised surface hardness variation by light grinding of the side faces of the cut area or possibly flame-softening have been found to be effective ways of minimising this risk. Another method that has been described as effective is the welding of a bead along the edges of a flame-cut cope, which reheats the area and may relieve some of the residual stress near the cope edges⁴. However, it has been demonstrated that observing these provisions (a, b and c above) in the cutting of the cope is the key factor in the control of cracking.

The drilling of holes in “K-areas” should be avoided because it is known that they can similarly be responsible for crack initiation. If transverse stiffeners, plates etc. have been welded to the beam across the web and venting is necessary, this should be done in the stiffener or plate, and not in the “K-area” of the beam.

2.10 Cold forming

Compliance with the requirements of EN 10025 regarding strain limits will avoid cracks during galvanizing originating at plastic notches and defects due to cold forming.

3 Guidance - galvanizing process

3.1 Use of alloying elements in the galvanizing bath

The level of tin, bismuth and lead in the galvanizing bath is known to have an influence on LMAC occurrence when susceptible components are galvanized. In particular, levels of tin in excess of 1% in combination with elevated levels of lead and bismuth have been observed to lead to significant cases of LMAC in certain large structures.

In the first instance, bath composition will meet the requirements for bath composition given in EN ISO 1461.

For galvanizing of the vast majority of constructional steelwork (inspection zones 1 and 2 in Annex I), where high levels of component strain are not experienced during dipping, it is recommended that, in addition to the requirements of EN ISO 1461, the combined levels of tin, bismuth and lead shall not exceed 1.0%.

For galvanizing of more susceptible structural steelwork (inspection zone 3 in Annex I) where other parameters may create a susceptibility to LMAC, it is prudent to operate the galvanizing bath with tighter controls on certain alloying elements, as given in Table 1.

Table 1

	Maximum composition in galvanizing bath (wt%)
Sn	≤ 0.1%
Pb + 10Bi	≤ 1.5%

The recommendations given in Table 1 would also be appropriate to inspection zones 1 and 2 in Annex I.

Industrial experience has demonstrated that other commonly-used alloy elements (e.g. Ni and Al), when used at levels in common industrial practice, do not influence LMAC occurrence.

3.2 Control of the strain in the steel component during galvanizing

The highest possible immersion speed and highest dipping angle should be used, without compromising the safety of operators and equipment. The use of higher dipping speeds will be dependent on the adequacy of venting and geometry of the component (see 2.8).

Any impediments to rapid immersion (poor venting, inappropriate provision for suspension of the component) should be identified, reported and corrected.

Where possible, the component should be pre-heated (by heated pre-flux and/or drier where appropriate) to minimise thermal gradients during immersion in the bath.

3.3 Duration of immersion in the galvanizing bath

The holding time in the galvanizing bath should be kept as low as feasible. If the holding time exceeds 30 minutes, a higher level of post-galvanizing inspection should be agreed.

4 Post-galvanizing inspection

Any requirement for post galvanizing inspection and/or certificate of compliance with EN ISO 1461 should be agreed at the time of order (as set out in EN 1090-2: 2011, F7.4). The standard requires that post galvanizing inspection is carried out unless it is otherwise agreed.

Visual inspection should be applied unless otherwise agreed between steelwork contractor and galvanizer. Inspections should be carried out by suitably qualified personnel.

Where there is a particularly critical or susceptible detail or when the consequences of structural failure of a single member is sufficiently high, the Engineer should consider whether the risk of LMAC is such as to warrant any post-galvanizing inspection in addition to the visual inspection.

Table 2 Post-Galvanizing Inspection (refer also to Annex 1)

Post Galvanizing Inspection Reference	Level of Inspection
Inspection Zone 1	Visual inspection of all accessible surfaces of components and joints. The inspector should be suitably qualified and should be familiar with the fabrication details and possible crack initiation sites. Inspection records should be produced and made available to the Engineer when requested. Any further defects or indications shall be reported immediately and further inspection (NDT) used to verify the report. If cracking is confirmed then an inspection schedule shall be developed for all steelwork to ensure that other members are free of cracks.
Inspection Zone 2	Non-destructive testing (NDT) generally on areas where defects have been found through visual inspection or other areas identified by the Engineer either in the Project Specification or noted on drawings.
Inspection Zone 3	Systematic non-destructive testing (NDT) for areas identified by the Engineer either in the Project Specification or noted on drawings.

Any additional inspection required by the Engineer should form part of the Project Specification.

The Steelwork Contractor must ensure that any agreed post galvanizing inspection is completed, although it may be delegated to a subcontractor, the galvanizer or some other competent agency. The detailed inspection regime on the post-galvanized structure should be as detailed in the Project Specification.

The recommended inspection regime, which should take place as soon as possible after galvanizing, is shown in table 2. As a minimum, visual inspection of all accessible surfaces is recommended. This may be followed by a more detailed inspection using non-destructive testing if cracks are identified during the visual inspection.

The choice of inspection regime should be made with reference to Annex I.

The areas to be visually inspected should be defined by the Engineer taking in to account the type of structure and the criticality of the members. Particular attention should be paid to inspecting likely crack initiation sites such as welds, corners, gas-cut edges, holes etc.

Consideration should be given in the quality plan, to critical or sensitive areas of the fabrication that might be subject to higher levels of post-galvanizing inspection in the event that defects are found. This should be specified by the Engineer in the Project Specification.

Visual inspection is very effective for identification of significant cracking but for smaller cracks that cannot be detected by visual inspection, NDT systems are required. The use of additional NDT would not normally be considered unless there is evidence of a susceptibility to cracking and then it should be targeted at the areas where cracks have been identified.

The most suitable NDT techniques are magnetic flux tests (MT) according to EN ISO 9934-1 to 3 that take account of:

- the reduced sensitivity from coat thicknesses $t_{zn} \geq 50 \mu\text{m}$ (Section 7, EN ISO 9934-1)
- limited accessibility in the area of spandrels from web, flange and endplates.

Satisfactory MT-Testing, for typical hot dip galvanized coating thicknesses as normally observed on structural steelwork, can be achieved by magnetization with electric flux, magnetic yoke or by hand-magnets. A sufficient magnetization time of 6 s and a subsequent post magnetization time of 6 s would provide sufficient time for the formation of indications. The magnetization should be checked by measuring the tangential magnetic field strength as closely as possible at the surface on the basis of the Hall-effect, which should attain a value of 4 kA/m (40 A/cm). The documentation of the tests should comply with the requirements in EN ISO 9934-1.

References

- 1 EN ISO 14713: 1999, 'Protection against corrosion of iron and steel in structures – zinc and aluminium coatings – Guidelines'.
- 2 A 143-74 (Re-approved 1989), 'Standard practice for safeguarding against embrittlement of hot dip galvanized structural steel products and procedures for detecting embrittlement', ASTM
- 3 Langill T. J., and Schafly T 'Cope cracking in structural steel after galvanizing', Modern Steel Construction, 1995, vol. 35, pp40-43
- 4 ASTM A 385-05 'Practice for Providing High-Quality Zinc Coatings (Hot-Dip)'

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Selection of Detail Class

Detail Class	Detail Description	Inspection Zone	Inspection Requirements
A	1 Free beam end	Inspection Zone 1	only visual inspections are necessary
	2a Transverse stiffener connected to 2 edges (end distance $e > h/2$)		
	2b Transverse stiffener connected to 3 edges (without cut outs)		
	2c Transverse stiffener with flange connected to 3 edges (without cut outs)		
	3 Full endplate		
	Holes in the web at the end of the beam with diameter $d \geq 25\text{mm}$		
	4 Transverse stiffener attached to the flange		
	8 Welded shear studs		
B	1a Drainage holes in the web	Inspection Zone 1	only visual inspections are necessary
	1b Holes in the web at the end of the beam with diameter $d \leq 25\text{mm}$		
	2 At full weld around fin plates or gusset plates		
	3 Cope out $r = 10\text{ mm}$, $l_{\text{cope}} < 150\text{ mm}$		
	4 Transverse stiffener connected to 2 edges (with cut outs)		
	5 Transverse stiffener connected to 3 edges (with cut outs)		
	6 Transverse stiffener with flange connected to 3 edges (with cut outs)		
	7 At intermittent welds of attachments		
	9 At full welding of attachments in the web		
C	1 At the weld around plates inserted into the webs of profiles or into tubes	Inspection Zone 1	only visual inspections are necessary
	2 In the web of slender profiles below half cover end plates		
	3 Cope out $r < 10\text{ mm}$, $l_{\text{cope}} > 150\text{ mm}$		

Annex I - Guidance on selection of post-galvanizing inspection requirements

The designer or fabricator should classify the prefabricated steel component to be zinc coated, according to the strain requirement during dipping into:

- Construction Class I, II or III (related to profile depth, material strength and toughness of material).
- Detail Class A, B or C (related to peak values of local strain requirements)

For complex prefabricated structural components, the 'Detail Classification' may be performed considering all details of connection by using the class for the most onerous detail as representative for the whole steel component.

Construction Class	Steel grade	Inspection Zone	Reference value h of profile depth [mm]
I	S460	Inspection Zone 1	$h_c = 480$
	S355		
	S275		
	S235		
II	S460	Inspection Zone 2	$h_c = 300$
	S355		
	S275		
	S235		
III	S460	Inspection Zone 3	$h_c = 480$
	S355		
	S275		
	S235		

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